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MINIMAL SUPERSTRING STANDARD MODEL: A REVIEW*

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I review a heterotic–string solution in which the observable sector effective field theory just below the string scale reduces to that of the MSSM, with the standard observable gauge group being just $SU(3)_C \times SU(2)_L \times U(1)_Y$ and the $SU(3)_C \times SU(2)_L \times U(1)_Y$–charged spectrum of the observable sector consisting solely of the MSSM spectrum. Associated with this model is a set of distinct flat directions of vacuum expectation values (VEVs) of fields that all produce solely the MSSM spectrum. Some of these directions only involve VEVs of non–Abelian singlet fields while others also contain VEVs of non–Abelian charged fields. The phenomenology of theses flat directions is summarized.

1. Minimal Superstring Standard Model

The most realistic string models found to date have been constructed in the free fermionic formulation[1] of the heterotic–string. A large number of three generation models, which differ in their detailed phenomenological characteristics, have been built.[2] All these models share an underlying $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold structure, which naturally gives rise to three generations with the $SO(10)$ embedding of the Standard Model spectrum.[3] In some of these models the observable sector gauge group directly below the string scale is a Grand Unified Theory, while in others it is the (MS)SM gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$, joined by a few extra $U(1)$ symmetries. In chiral three generation models of the latter class, one of the additional Abelian gauge groups is inevitably anomalous. That is, the trace of the $U(1)_A$ charge, $\mathrm{Tr}\, Q^{(A)} \neq 0$, generates a Fayet–Iliopoulos (FI) term, $\epsilon \equiv (g_s^2 M_P^2/192\pi^2)\mathrm{Tr}\, Q^{(A)}$.

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The FI term breaks supersymmetry near the Planck scale, and destabilizes the string vacuum. Supersymmetry is restored and the vacuum is stabilized if there exists a direction, $\phi = \sum_i \alpha_i \phi_i$, in the scalar potential which is F–flat to sufficient order (general arguments suggest this means to at least 17^{th} order), and also D–flat with respect to all non–anomalous gauge symmetries, and in which $\sum_i Q_i^{(A)} |\alpha_i|^2$ and ϵ are of opposite sign. If such a direction exists it will acquire a VEV cancelling the anomalous D–term, restoring supersymmetry and stabilizing the string vacuum.

In addition to possessing an anomalous $U(1)_A$ symmetry, chiral three generation $SU(3)_C \times SU(2)_L \times U(1)_Y \times \prod_i U(1)_i$ string models generically contain numerous non–MSSM $SU(3)_C \times SU(2)_L \times U(1)_Y$–charged states, some of which only carry MSSM$\times \prod_i U(1)_i$ charges and others of which also carry hidden sector (non)–Abelian charges. Recently, we showed that in some of these models it is actually possible to decouple all such non–MSSM states from the low energy effective field theory. For example, in the "FNY" model first presented in Ref. 4, we discovered there are several flat directions[5,6] for which almost all MSSM–charged exotics receive FI masses (typically of the scale 5×10^{16} GeV to 1×10^{17} GeV) while the remaining MSSM–charged exotics (usually composed of simply a $SU(3)_C$ triplet/anti–triplet pair) acquire masses slightly suppressed below the FI scale by a factor of $\mathcal{O}(\frac{1}{10}$ to $\frac{1}{100})$. Some of our flat directions accomplishing this feat contain only VEVs of non–Abelian singlet fields[6,7] while others of ours also contain VEVs of non–Abelian charged fields[8,9]. Along these directions, exactly three generations of (Q_i, u_i^c, d_i^c, L_i, e_i^c, N_i^c) fields and a pair of electroweak Higgs, h_u and h_d, are the only MSSM–charged fields that remain massless significantly below the FI scale. The non–MSSM–charged singlet fields and hidden sector non–Abelian fields that also remain massless below the FI scale vary with the flat direction chosen.

2. Flat Direction Phenomenology

The complete massless spectrums and superpotentials through sixth order resulting from the anomaly-cancelling singlet and non-Abelian flat directions appear, respectively, in Refs. 7 and 10. In all of the singlet directions and in many of the non-Abelian flat directions, the leading mass terms were found to be $Q_1 u_1^c \bar{h}_1$ and $Q_3 d_3^c h_3$. In other words, the left–handed components of the heaviest up-like and down-like quarks live in different multiplets. Thus, these directions possess the phenomenological problem of effectively interchanging the strange and bottom masses. Importantly, several non-Abelian flat directions do not present this difficulty and appear to offer much more viable phenomenology.

We have discovered that a few extra Abelian symmetries usually survive along both singlet and non-Abelian flat directions. Generically, these extra local $U(1)_i$ could not have been embedded in $SO(10)$ or E_6 GUTS.[9] Relatedly, a common feature in the surviving $U(1)_i$ combinations is a flavor non–universality. Thus, the distinctive collider signatures of a Z' arising from one such symmetry will be a non–universality in the production of the different generations. An additional Z' of this type has also been suggested as playing a role in suppressing proton decay in supersymmetric extensions of the Standard Model.[11]

Another very interesting aspect of our non-Abelian flat directions is that the related Higgs mass eigenstates, h_u and h_d, each contain several components, with the weights of the components often varying by several orders of magnitude. Furthermore, different quark and lepton generations couple to different Higgs components. Thus, even when all three generations of quark and lepton mass terms result from low order superpotential terms, a natural generational mass hierarchy appears. This could provide a novel explanation for the approximate $10^{-5} : 10^{-3} : 1$ generational mass ratio.

In Ref. 7 we presented several reasons why non-Abelian VEVs are, ideed, likely required for a phenomenologically viable low energy effective MSSM, at least for the FNY string model. Evidence has also been presented in the past suggesting this might be true as well for all string-derived MSSM $\mathbb{Z}_2 \times \mathbb{Z}_2$ models. This implies that there is truly significant worth in exploring the generic properties of non-Abelian flat directions in $\mathbb{Z}_2 \times \mathbb{Z}_2$ models that contain exactly the MSSM three generations and two Higgs doublets as the only MSSM–charged fields in the low energy effective field theory.

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References

1. I. Antoniadis, C. Bachas, and C. Kounnas, *Nucl. Phys.* **B289** (1987) 87;
   H. Kawai, D.C. Lewellen, and S.H.-H. Tye, *Nucl. Phys.* **B288** (1987) 1.
2. I. Antoniadis, J. Ellis, J. Hagelin, and D.V. Nanopoulos, *Phys. Lett.* **B231** (1989) 65;
   J. Lopez, D.V. Nanopoulos and K. Yuan, *Nucl. Phys.* **B399** (1993) 654;
   I. Antoniadis. G.K. Leontaris and J. Rizos, *Phys. Lett.* **B245** (1990) 161;
   G.K. Leontaris, *Phys. Lett.* **B372** (1996) 212;
   G.K. Leontaris and J. Rizos, *Nucl. Phys.* **B554** (1999) 3;
   A.E. Faraggi, *Phys. Lett.* **B274** (1992) 47; *Phys. Lett.* **B278** (1992) 131; *Nucl. Phys.* **B387** (1992) 239; *Phys. Lett.* **B339** (1994) 223.
3. A.E. Faraggi and D.V. Nanopoulos, *Phys. Rev.* **D48** (1993) 3288;
   A.E. Faraggi, hep-th/9511093; hep-th/9708112.
4. A.E. Faraggi, D.V. Nanopoulos, and K. Yuan, *Nucl. Phys.* **B335** (1990) 347;
   A.E. Faraggi, *Phys. Rev.* **D46** (1992) 3204.
5. G.B. Cleaver, A.E. Faraggi and D.V. Nanopoulos, *Phys. Lett.* **B455** (1999) 135, hep-ph/9811427;
   G.B. Cleaver, "M-Fluences on String Model Building," CTP-TAMU-46/98, hep-ph/9901203, Proceedings of CPT '98, November, 1998, Bloomington, Indiana.
6. G.B. Cleaver, A.E. Faraggi and D.V. Nanopoulos, "A Minimal Superstring Standard Model I: Flat Directions," ACT-2/99, CTP-TAMU-12/99, TPI-MINN-99/22, UMN-TH-1760-99, hep-ph/9904301. To appear in *Int. J. Mod. Phys.* **A**.
7. G.B. Cleaver, A.E. Faraggi, D.V. Nanopoulos, and J.W. Walker, "A Minimal Superstring Standard Model II: A Phenomenological Study," ACT-9/99, CTP-TAMU-37/99, TPI-MINN-99/46, UMN-TH-1821-99, hep-ph/9910230. To appear in *Nucl. Phys.* **B**.
8. G.B. Cleaver, A.E. Faraggi, D.V. Nanopoulos, and J.W. Walker, "Non-Abelian Flat Directions in a Minimal Superstring Standard Model," *Mod. Phys. Lett.* **A15** (2000) 1191, hep-ph/0002060.
9. G.B. Cleaver, A.E. Faraggi, D.V. Nanopoulos, and T. ter Veldhuis, "Towards String Predictions," ACT-4/00, CTP-TAMU-07/00, OUTP-00-04P, TPI-MINN-00/06, UMN-TH-1842-00, hep-ph/0002060.
10. G.B. Cleaver, A.E. Faraggi, D.V. Nanopoulos, and J.W. Walker, "Phenomenology of Non–Abelian Flat Directions in a Minimal Superstring Standard Model," To appear.
11. J. Pati, *Phys. Lett.* **B388** (1996) 352, hep-ph/9607446.